6. Human Factors and Human Reliability in Healthcare and Nuclear Power

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ABSTRACT

There are numerous human factors and human reliability issues facing the nuclear power and healthcare industries. This chapter focuses on the challenges that are common to both industries, while also touching upon their unique strengths and areas where improvements are most needed. The chapter concludes with a discussion of human factors areas in which each industry might gain valuable insights from the other and areas for potential future collaboration.

KEY POINTS

- The nuclear and healthcare domains depend on human beings to perform safety critical tasks in complex work environments making it essential for these industries to address human factors and human performance issues effectively in order to reliably achieve safe and successful outcomes.
- Both domains share the need to make advances in their processes for introducing new technology, developing and managing the knowledge residing individually and collectively in their human resources, and optimizing their use of automation.
- Although consideration must be given to the differences between the industries' work, cultural, economic, and regulatory environments, opportunities are available to make advances through information exchanges and by leveraging collective resources in areas with shared needs and common objectives.

INTRODUCTION

An important insight from studies of the Three Mile Island (TMI), Chernobyl, and other nuclear power plant (NPP) events is that errors resulting from human factors deficiencies such as poor interface design, deficient procedures, and inadequate training are a significant contributing factor to NPP incidents and accidents. In the healthcare industry, the importance of human performance, and more specifically the toll of human error, is equally evident.

The Institute of Medicine (IOM) report, *To Err Is Human: Building a Safer Health System,*[1] noted that more people die in a given year as a result of medical errors than from motor vehicle accidents (43,458), breast cancer (42,297), or AIDS (16,516). Total national costs (lost income, lost household production, disability and healthcare costs) of preventable adverse events (medical errors resulting in injury) were estimated to be between $17 billion and $29 billion, of which healthcare costs represent over one-half.

Insights such as these are motivating professionals in both industries to increase their focus on understanding the mechanisms and conditions that lead to human error in the workplace and identifying the means to improve outcomes. The objective and potential of these efforts are substantial improvements in public health and safety.

Optimizing the performance of systems that rely on human performance is a primary objective and principal activity of human factors and human reliability professionals. The field of human factors, also known as ergonomics, is diverse and multidisciplinary. Although the field has been defined and described in many ways, the following definition, which was developed by the International Ergonomics Association and adopted by the Human Factors and Ergonomics Society, adequately describes "human factors" as the term is used in this paper.

> Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. Ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people.[2]

To put it more simply, human factors professionals use their knowledge of the strengths and limitations of human performance, including cognitive performance (e.g., decision making) to achieve an integrated system that optimizes both human well-being and system performance.

A principal activity of human reliability professionals is human reliability analysis (HRA). HRA is a highly structured analysis of human interactions with a system to identify the types and likelihood of human errors that contribute to system failures. Human reliability analysts employ a wide range of methods producing both quantitative results and qualitative insights that help to prospectively assess and improve the performance and safety of systems.

One of the key benefits of HRA, when conducted as part of probabilistic risk assessment (PRA), is identifying which human errors are most likely under the anticipated operating conditions, which errors are recoverable or nonrecoverable given the overall system design, including any physical or procedural safeguards, and which actions have the greatest potential for undesirable system outcomes.

Working together, human factors and human reliability professionals can bring a powerful set of tools that can be used to understand and improve, in a structured, rigorous, and targeted manner, the functioning of complex systems that rely to some measure on human performance. Nuclear power plant control rooms and hospital settings such as surgical suites or intensive care units may differ in the extent to which they rely on technology and automation versus skilled human performance. Nevertheless, in the final analysis, both are heavily dependent on human beings executing complex work, making human factors and human reliability critical for each to reliably achieve safe/successful outcomes.

An outline of how human factors and human reliability can be effectively brought together is described in a guideline used widely in the nuclear power industry, NUREG-0711, "Human Factors Engineering (HFE) Program Review Model."[3] Although it was written as a review guideline for use by U.S. Nuclear Regulatory Commission (NRC) technical staff, NUREG-0711 defines the elements of an effective HFE program, one of those elements being HRA, and describes the relationships between the elements. The guideline has become the NRC's primary tool in ensuring that commercial nuclear power plant control rooms are developed and, as necessary, modified in conformance with a process that ensures an effective integration of the human and technological components of a system.

Other elements of an effective HFE program described in NUREG-0711 include: HFE program management, operating experience review, functional requirements analysis and function allocation, task analysis, staffing, human-system interface design, procedure development, training program development, human factors verification and validation, design implementation, and human performance monitoring.

Similar standards for human factors engineering, IEC/ISO 62366:2007, *Medical devices—Application of usability engineering to medical devices,*[4] and ANSI/AAMI HE75:2009, *Human factors engineering—Design of medical devices,*[5] exist for the design and deployment of medical devices (but not medical processes or procedures constituting "the practice of medicine"). IEC/ISO 62366:2007, a consensus international standard, addresses all aspects of the process of user interface design and evaluation. A separate international standard, ISO 14971:2012, *Medical devices—Application of risk management to medical devices,*[6] addresses the risk management process for the design of medical devices.

The HFE program elements described in these documents have an important role in ensuring success in optimizing human well-being and system performance. However, when it comes to implementing these elements, each presents its own unique challenges. These challenges are highlighted in the following discussion of thorniest issues, where the reader may note that many of the issues correspond to the previously listed elements of an effective HFE program.

Effectively implementing these elements depends not only upon applying state-of-the-art human factors and human reliability principles and practices, but also other factors such as the availability of resources and applicable operating experience, system complexity, diversity, and stability, and economic and regulatory incentives. As such, whereas the nuclear and healthcare industries share a common need and interest to effectively manage complex, human-dependent systems, each industry's relative strengths and weaknesses, and therefore specific challenges and opportunities, is shaped by these other factors.

THORNIEST ISSUES

Since real-time operations in running a nuclear reactor and in many dynamic arenas of healthcare (such as the operating room, intensive care unit, or emergency department) depend on the correct and reliable performance of personnel, both as individuals and as teams, there is a set of thorny issues concerning human performance that is common to both of these dynamic settings.

One way to look at these issues, or common human reliability and human factors challenges, is to consider that in both settings it is critical to get the right information to the right people, so that they can make the right decision and take the right actions at the right time. In addition, since both industries have critical roles in, or implications for, public health and safety, it is essential that work is conducted within a safety culture that prioritizes and effectively supports meeting these obligations to the public.

One overarching issue is the intrinsic limitations of human beings and their susceptibility to certain performance-shaping factors—the human reliability side. In general, the two industries can expect that, on any given day, most of their personnel will be capable, appropriately trained, and intent on performing well. However, even with the best of intentions, real people, living in the real world, will not be perfect.

Each industry must cope with the fact that everyday performance will be degraded by a variety of factors both external and internal to the individual such as excessive workload or cognitive biases. Some of these factors are, in principle, reducible, while others may be irreducible. The impact on human performance of fatigue, illness (e.g., the common cold), and life stresses might be reducible to some degree, but can never be completely eliminated. This does not mean that such factors are ignored by human factors and human reliability professionals. Rather, in such circumstances, the focus typically shifts to other means of mitigating their effects, such as through preventive measures or design decisions that reduce the potential impacts of degraded human performance on overall system performance.

One challenge that both industries face is that our understanding of the effects of such performance-shaping factors on human performance, including the performance of safety critical tasks in the nuclear and healthcare industries, is incomplete. Academic psychology studies typically use college students as subjects, whereas the military amasses similar data mostly from young soldiers. There is less information about the work psychology of middle-aged and older people who are often involved in real-time operations in the nuclear power and healthcare industries.

The demographics of the workforce in the two industries differ significantly. The peak growth of the nuclear power industry occurred in the 1960s and 1970s (prior to the accident at Three Mile Island) and many key personnel began work in that era and are now in the latter portion of their careers. Healthcare has a mixed-age workforce whose composition is affected by diverse factors including changes in scope of practice for clinicians and the general economy's impact on decisions to retire.

In general, we know that as personnel become older, they may be more vulnerable to fatigue or to demands on memory and speed of action, although this vulnerability may be offset by their greater experience. However, determining "fitness for duty" is a complex issue, both in terms of physiological and cognitive measurement and in relating any such results to the practicalities of running a power plant or a hospital. In short, better fundamental data on human performance and reliability, especially in populations of individuals of the proper age and gender mix to match the actual workforce, would be highly desirable for both industries.

Some performance decrements are inherent to fundamental human psychology. In particular, "prospective memory"—the memory of an intention to do something in the future—is particularly vulnerable to disruption by distractions and interruptions. Distractions can kill. Unfortunately, as technology increases our access to greater amounts of information, it can also contribute to more complex work processes with more opportunities for distraction and interruption.

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In the nuclear industry, a perennial challenge is appropriately distributing fixed training resources between addressing the effective response to low-probability, high-consequence events versus maintaining skill in performing routine tasks. This challenge will likely rise as the industry grapples with the lessons learned from the tsunami that devastated the Fukushima Daiichi nuclear power plant in Japan and seeks to improve the ability of operators to perform under similar catastrophic circumstances.

In healthcare, the use of simulation—beyond simple "dolls" and part-task and procedure trainers—is less than 25 years old and is achieving more widespread use only in the last decade. Even so, the use of healthcare simulation remains spotty. At present, simulation training is mostly used with early learners—medical or nursing students, and interns/residents (physicians who are learning a specialty mostly by an apprenticeship process of taking care of real patients).

The penetration of meaningful simulation to experienced personnel is still very low, although the field is growing rapidly. However, there are many barriers to achieving an embedding of frequent simulation training into the fabric of healthcare similar to that in nuclear power.

While the issue of training for both normal operations and response to adverse events is quite broad in scope (see below), one aspect is directly applicable to the issue of human factors of device use, and is much more significant in healthcare than in other industries.

As indicated above, the number of healthcare workers is very large and the number of different devices in use is also very large. Some new piece of equipment is introduced into any given unit of a hospital every few months, and the replacement cycle for equipment costing up to around $100,000 is often no greater than seven years.

Ensuring that all personnel are fully trained in the use of life-critical equipment is a major challenge. In general, nursing does a better job of this than medicine, but typically any training provided to personnel prior to their use of new devices is perfunctory at best and does not guarantee their ability to use the equipment in all situations or modes, or to handle errors, glitches, or failures. In contrast, this problem does not exist with nuclear technology, where control systems are introduced slowly and in an integrated fashion and where training of users is mandated and reliably performed.

Decision making in complex dynamic worlds is a key issue in both domains, where critical things can happen in seconds to hours, not in days to years (although each domain has other settings or conditions where slower evolution is the norm). Some decisions are made solely by individuals, but more typically dynamic decisions are made, and actions taken, by a real-time multidisciplinary team.

Both industries have benefited from the literature on naturalistic decision making[8,9] and the cognitive psychology of real-time work, envisioning a repeated loop of observation, decision, action, and reevaluation, for which a variety of models and acronyms have been proposed. Both industries recognize the Recognition-Primed Decision model espoused by Gary Klein.[10,11]

Issues of both dynamic decision making and teamwork/team management are covered in team-oriented training paradigms such as Crew Resource Management (CRM). While originally they were conducted in "seminar fashion," the trend in most industries using the CRM approach has been to link it to realistic simulations.

This has been done in healthcare (starting with Gaba's group at VA Palo Alto/Stanford University in 1990) and has spread significantly in healthcare, but the vast majority of clinicians have not yet experienced this training. CRM has been used in nuclear power, but its use is not yet common.[12]

Thus, there is still a considerable amount to accomplish in simulation-based CRM or team training in both industries. Moreover, neither industry yet knows with certainty how to ensure optimal decision making. There are general principles, some of which have been translated effectively into training paradigms and actual emergency response behaviors.

Still uncertain in both domains is which type of CRM or team training is optimal, how often it needs to be conducted, how critical simulation is to the different elements of the training, and the correct mix of training for specific disciplines (or control positions) versus combined team training for all personnel. Further investigation of these and other strategies to improve decision making by individuals and teams would be beneficial to both domains.

An important aspect of optimal human performance in both industries, and a key element of the "collective system," is the safety culture within which personnel work. Though elements of morale and esprit de corps have long been known to be critical to effective work, safety culture as an entity in industries of intrinsic hazard was largely highlighted by the nuclear power industry in the late 1980s, in the aftermath of the 1986 Chernobyl nuclear accident.

The NRC issued its first policy statement on safety culture in 1989 and has since enhanced its reactor oversight process to more fully address safety culture. Today, the NRC defines nuclear safety culture as the core values and behaviors resulting from a collective commitment by leaders and individuals to emphasize safety over competing goals to ensure protection of people and the environment.

Similarly, the concept of safety culture was introduced in healthcare during the late 1980s and has been highlighted in other settings through highly public incidents such as the Challenger (1986) and Columbia (2003) space shuttle accidents.

Although there is widespread agreement that an adverse culture that does not promote and reward safety practices can be strongly corrosive to safety, there are many different formulations of the issues of safety culture. Even within the single rubric of "high-reliability organization theory," there are a variety of approaches to considering safety culture.

Many distinguish between safety "climate" and the actual "culture" in the workplace. The latter can probably only be investigated using anthropological and ethnographic methods (e.g., by "embedding" trained but neutral observers into various parts of the organization)—a very expensive and time-consuming approach.

Instead, most studies have used the surrogate of "safety climate," which can be thought of as the surface features of the underlying culture that are amenable to simpler probing strategies, as through written questionnaires. Although surveys are far faster and less expensive to conduct. their validity or their ability to pinpoint the state of an organization's safety culture, or to predict the best type of interventions to improve safety, are all debatable.

While considerable attention has been devoted to a culture of "reporting" of safety issues or incidents, safety culture extends beyond merely willingness to report. Critical aspects that seem applicable to both domains include the following:

1. **Values**, such as considering safety as a primary priority equaling or exceeding efficiency/production, or a preoccupation with risk of failure rather than prior success.

2. **Beliefs**, such as that safety must be actively managed and does not emerge simply from "good people doing their jobs properly," or that processes are more important than individual skill.

3. **Work norms**, such as that people speak up about safety regardless of hierarchy, that they are encouraged to call for help early and this happens frequently, that there is explicit communication across all personnel, or that they are rewarded for rationally erring on the side of safety even when their credible concerns turn out to be wrong.

For the U.S. nuclear power industry, nine traits of safety culture are highlighted in NRC's Safety Culture Policy Statement[13]:

- Leadership Safety Values and Actions—Leaders demonstrate a commitment to safety in their decisions and behaviors.
- Problem Identification and Resolution—Issues potentially impacting safety are promptly identified, fully evaluated, and promptly addressed and corrected commensurate with their significance.
- Personal Accountability—All individuals take personal responsibility for safety.
- Work Processes—The process of planning and controlling work activities is implemented so that safety is maintained.
- Continuous Learning—Opportunities to learn about ways to ensure safety are sought out and implemented.
- Environment for Raising Concerns—A safety-conscious work environment is maintained where personnel feel free to raise safety concerns without fear of retaliation, intimidation, harassment, or discrimination.
- Effective Safety Communication—Communications maintain a focus on safety.
- Respectful Work Environment—Trust and respect permeate the organization.
- Questioning Attitude—Individuals avoid complacency and continuously challenge existing conditions and activities in order to identify discrepancies that might result in error or inappropriate action.

To our knowledge, there have not been specific comparisons of hospital safety climate to that in nuclear power plants. However, there have been comparisons of hospital safety climate to that in naval aviation (both carrier-based and shore-based). In a nutshell, the measures of safety climate, on matched questions, showed that only 1–2% of hospitals achieved a climate similar to that in naval aviation, and on aggregate the climate measure was about three times worse in hospitals than in naval aviation.[14,15] This shows that healthcare has a long way to go to achieving the high reliability organizational status it seeks, and also suggests that directly comparing safety climate and safety practices in nuclear power plants with those in hospitals would be a benchmarking exercise that could be useful for identifying areas for improvement in both industries.

Another human performance issue with both commonalities and differences between the nuclear power and healthcare industries is the use of emergency response procedures. The response of a nuclear power plant control room crew to an event that challenges the safety of the plant is driven almost entirely by procedure. These procedures can be quite detailed, highly prescriptive, and in some circumstances complex. To support effective human performance, emergency operating procedures (EOPs) are developed in accordance with a writer's guide to ensure consistency in language, structure, and format and the application of human factors design principles.

In addition, the use of symptom-based EOPs marks a significant development in emergency procedure design. Symptom-based EOPs alleviate the need for operators to correctly diagnose the cause of anomalous indications in order to maintain plant safety, but rather allow them to address a range of failures by focusing on the maintenance of the plant's critical safety parameters. In so doing, symptom-based EOPs address the types of misdiagnosis failure that contributed to melting the reactor core in the 1979 nuclear power plant accident at Three Mile Island. Despite these practices and gains, the nuclear power industry faces new challenges for designing effective procedures.

As the nuclear power industry constructs new plants, it is transitioning from paper-based to computer-based procedures and finding it necessary to address a host of design issues with significant implications for human performance. In addition, the industry is also in the process of considering the lessons learned from the Fukushima Daiichi nuclear power accident, including the implications for emergency procedure design. As a consequence, a future area of emphasis will be better integrating procedures for the types of events which were anticipated during design, and for which the safety systems were constructed, with procedures that provide operators the flexibility to creatively respond to catastrophic events including those outside original design intent by using all available resources at their disposal.

In healthcare, other than for cardiac life support and acute trauma management, the use of widely accepted explicit emergency response procedures and written/graphical cognitive aids articulating responses to possible emergency situations is in its infancy. Even in fields like anesthesiology, where such procedures have been advocated, only a handful are in widespread use and they have not undergone a design and validation process to ensure optimal human performance.

Notwithstanding recent research, including simulation studies showing that use of cognitive aids improves response to uncommon critical events, it may be a long time before there is wide adoption of cognitive aids in healthcare. Both industries may benefit from working on methods to optimize procedures for use by time-pressured professionals during unexpected or rare critical events.

Interestingly, both industries have relatively low levels of automation. In the U.S. nuclear power industry, the fleet of reactors currently operating is largely controlled by analog systems requiring manual control by operators of discrete systems. Safety systems are initiated automatically when plant parameters exceed specified set points, but their continued functioning typically requires manual control. Major plant evolutions such as start-up and shutdown are done manually at U.S. nuclear power plants and at most others worldwide. The automation that exists is system-centric and often shows little attention to human factors. Future NPPs in the U.S. represent an opportunity to address some of these shortcomings by using highly-integrated digital control rooms that incorporate human factors principles during the design process, rather than only as a corrective action.

In healthcare, some basic functions are partially automated (e.g., mechanical ventilators, intravenous medication infusion pumps), but the automation is largely at the individual device level. Both nuclear power and healthcare are extremely conservative about closed-loop control of critical systems. In healthcare, there has been considerable research on closed-loop control of real-time drug delivery for potent medications such as anesthetics or drugs to rapidly increase or decrease the blood pressure. However, in U.S. healthcare, the regulatory hurdles to approve closed-loop controllers are very high and the marketplace demand is weak given that many clinicians are skeptical of automation.

Both industries may benefit from further investigation of the best mix of manual control and automation. The 2009 Air France 447 crash into the Atlantic Ocean, in which the primary flight instruments and autopilot were fooled by iced-over airspeed sensors, has been cited by experts from both industries as an example of how real-time operators who routinely use and rely upon automated systems can have trouble adapting when the automation is suddenly not functioning properly.

In fact, the detailed report[16] discusses issues of computerized alarm and diagnostic advice that was difficult for the crew to interpret in a timely and cogent fashion. This suggests that other industries of intrinsic hazard besides nuclear power and healthcare struggle with similar issues of data display, alarms, automation, and decision support for crews in highly dynamic emergency situations.

In general, representatives from both industries believe that there has been insufficient understanding of actual work practices including successful and unsuccessful performance using technology.

A common phenomenon that has been specifically studied in healthcare[17] is that personnel often find workarounds to successfully and expeditiously complete the work when they are faced with systems obstacles, including imperfect technologies or challenging user interfaces. Such workarounds get the job done in the moment, but also mask the underlying system failure modes which then remain hidden and uncorrected. Users are reluctant to report technology problems and failures (reporting is time consuming), and when they do so the reports may not contain enough contextual information to delineate the flaws in the design.

Improved understanding of user performance might come from simulations with existing or new technologies that are specifically focused on understanding the demands of real work and its interplay with the use of devices and interfaces. Another approach would be to embed observers into the workplace who are savvy about both the nature of the clinical/operational demands and relevant human factors issues.

Although we have identified those areas that we believe present some of the greatest challenges to both the nuclear and healthcare industries, readers will no doubt be able to identify additional areas. Our objective, however, was not necessarily to be comprehensive, but rather to show that these shared challenges are indeed shared *opportunities*, as described in the following sections.

SHARED LEARNING AND PROMISING ADVANCES

One commonality between the nuclear power and healthcare domains that was only briefly touched upon was that both domains attract highly educated and creative professionals who work with exceptional dedication to those they serve and who embrace the notion of continuous improvement. As a result, each domain has made important advances in methods and technologies that could be beneficial if applied or adopted by the other.

What the Healthcare Industry Might Learn From the Nuclear Power Industry

Given the large capital costs that are associated with most nuclear power plant upgrades and the severity of potential accidents, the nuclear power domain tends to examine many issues systematically, Experts built up substantial expertise in methodologies for the design and evaluation of human-system interfaces, as well as the training of personnel and the analysis of operating experience.

The methods for design and evaluation of interfaces in the nuclear power domain are comparatively comprehensive. Considerable regulatory guidance is available to support practitioners in their analysis, design, and evaluation of technology. For instance, NUREG-0711 outlines an HFE program for the analysis, design, and validation of a technology, providing guidelines and criteria that are based upon many foundational and recent human factors studies. Similarly, NUREG-0700 provides HFE guidance on information display, user-interface interaction and management, controls, workplace and workstation design, and guidance on specific systems such as alarm and communication systems. There are also many other technical reports and academic literature examining the utility of displaying advanced graphics in supporting operators (e.g., configurable displays[18] or ecological interface design[19,20]).

Presently, and for a variety of previously cited reasons, the healthcare industry does not routinely design interfaces as systematically as in nuclear power plants. Thus, the medical industry can adapt the available guidance and research in the nuclear power domain to bring about a systematic approach to designing interfaces for new technology.

Of the various analysis methods commonly employed by the nuclear power industry, function allocation appears to be the most foreign or least practiced in the medical domain for supporting design or introduction of new technology. Function allocation is an analysis method for determining how best to assign functions between available computational and control resources (e.g., humans, hardware, and software) to maximize total system performance, based on performance comparisons between resource types, implementation and maintenance costs, and the complexity of cognitive support needed for human users.

Thus, function allocation influences many aspects of the overall system design including the design of displays and controls, necessary staffing levels, and the development of training requirements. The nuclear power domain has integrated function allocation into its system design process.

The medical domain could benefit from the application of this technique to optimize its mix of humans and technology.

Early designs of nuclear power plants were plagued with nuisance alarms during operations, especially during emergency conditions, motivating years of studies on operator responses to and management of alarms. In particular, alarm suppression according to modes or contexts of operations has been examined in full-scope simulator experiments. With the plethora of medical measurement devices in many types of acute patient care also leading to floods of alarms, healthcare should capitalize on this research and the lessons learned concerning effective alarm suppression.

The engineering of nuclear power plants naturally lends to the use of operating procedures. With several decades of operating experience, the nuclear power industry relies on procedures for both routine and nonroutine work of control room operators. In addition to common task-based procedures, symptom-based procedures are widely used to guide operating crews' responses to abnormal plant conditions. Although in healthcare high variability between patients constrains the application of strict procedures, improvements in the quality of healthcare in certain settings might be gained by taking advantage of the work done in the nuclear power domain to design procedures, particularly for nonroutine tasks.

The nuclear power industry also extensively employs full-scope simulators to establish and maintain the competence of control room operators for both normal and abnormal operations. The frequency of simulator-based training in the nuclear power industry, as part of an ongoing program of training and skill maintenance, generally exceeds that in any other safety critical domains. The high frequency of simulator use permits operators to rehearse procedural responses to rare events and gain familiarity with the effects of control actions untried in the physical plants.

As in aviation, demonstrating acceptable performance in simulation is the basis for operator relicensing. The healthcare domain is beginning to strive for analogous strategies of simulation training and assessment and can adapt the nuclear power industry's experience to its evolving simulation programs.

Even with substantive preventive measures in design, procedures, and training, the nuclear power industry encounters operational incidents and, on rare occasions, accidents. The nuclear power domain is generally effective at learning from operating experience by pursuing relatively blame-free and unbiased investigations of the causes of system failures with their *critical incident analysis*. In contrast, the healthcare domain is still burdened by concerns of blame and individual liability.

The healthcare industry is struggling to build robust structures for adverse event and near-miss reporting and for finding and sharing best practices and system solutions. Adopting some elements of these structures and practices from the nuclear power industry might be helpful to foster organizational learning. It should be noted that effective interface design often begins with a comprehensive operating experience review (OER). Advances in critical incident analysis can be expected to improve the scope and quality of information available for the OER and ultimately the quality of the interface design.

What The Nuclear Power Industry Might Learn From Healthcare

In healthcare, sites of practice are numerous and widely decentralized, exhibiting diverse and dynamic applications of evolving technology without the constraints of any extremely structured methodologies in analysis, design, and evaluation of technology. As a result, the healthcare industry deploys and reaps the benefits of new technology relatively quickly. One example of this is the use of high-definition monitors and multimodal displays that have yet to be tested and deployed in any U.S. nuclear power plants.

The nuclear power domain could benefit from increasing the pace of adopting new digital technologies to support operator work. The challenge for the nuclear power industry is how to adopt new digital technologies more quickly, while ensuring that such changes do not introduce unanticipated hazards such as unidentified failure modes. It would thus seem that methods and test beds for efficiently assessing new technologies and integrating them with the other elements of a plant's instrumentation and control system would be critical if the nuclear power industry is to reap more quickly the benefits of modern advances in digital technology.

Healthcare has recently begun to use simulation and simulators to address patient care processes in both routine and complex situations, for individuals as well as teams. An interesting application of simulation in healthcare is "in situ simulation" testing in which the patient simulator is brought to an actual work environment for assessing design and operational concepts early in the development cycle. This allows systems probing in the actual workplace, and is also conducive to testing of or training on new equipment, or even on prototypes that are not yet approved for use in clinical trials.

These kinds of uses of simulation contrast with the standardized training processes with high fidelity simulation in the nuclear power industry. The nuclear power industry may benefit from considering how analogous dynamic uses of simulation might be applicable.

RESEARCH AND IMPLEMENTATION NEEDS

The nuclear and medical industries offer each other different benchmarks and insights that can be used to improve research and practice of human factors and that highlight the different needs for the two respective domains.

When juxtaposed to healthcare, the nuclear power industry is often lagging behind in adoption of new technology to support operators. The speed at which new technology is adopted for safety critical applications is limited by the need to satisfy multiple stakeholders, including regulators, vendors, and utilities.

Going forward, more efficient processes will be necessary to evaluate and deploy equipment that takes advantage of the latest research and technology, especially if nuclear power is to remain cost-competitive with other energy sources. Critical to achieving meaningful advances will be research and methods that improve the ability to identify and understand the failure modes of advanced technologies as well as how designs can best support operator performance when the technology fails or its performance is degraded. One approach would be greater standardization on selection, development, and assessment of new technology.

On the other hand, healthcare is capable of adopting new technology at a fast pace, but the decentralized decision-making process leaves room for substantial improvement in the integration of technology in the work environment. Clinicians, biomedical engineers, and administrators can introduce new devices in various care units with inadequate consideration of the impact on care in that unit or on the overall institution particularly with regard to integration with other technologies. Though interoperability and networking standards/guidelines exist, addressing this decentralized decision-making process from a human factors perspective could improve the introduction of new technology. Hence, though coming from different starting points, it appears that both industries can benefit from improved standardization on selection and deployment of technology.

The integration of new technology in healthcare, especially hospitals, is hindered by a legacy operating model of the 19th century medical practice whose function allocations seem to be suboptimal for modern care models. Consequently, the distribution of responsibilities among workers or between humans and technology is sometimes dictated by traditions as opposed to structured analysis at the systems-design stage. In fact, the medical "system" was never designed—it simply evolved organically. The out-moded operating model is heavily entrenched in medical education, training, specialty oriented care, and hospital administration, thus constraining changes to function allocation. New human factors standards that have been promulgated recently (e.g., ANSI/AAMI HE-75:2009) offer some guidance on how to address this issue.

Healthcare urgently needs a more effective reporting infrastructure for analysis of accidents and incidents to improve organizational learning. The healthcare domain has been plagued by inadequacies in reporting, analysis, learning, and process improvement, due in large measure to the interaction of various unique intrinsic and organizational aspects of the industry and by the numerous stakeholders involved. This issue is discussed in detail in Chapter 8, Root Cause and Corrective Action.

Despite many differences, the nuclear and medical domains share some key similarities and thus some challenges that neither has successfully overcome. Workers in both industries are central to their effectiveness and operating cost; for both industries, labor costs dominate and rise with inflation over time. Unlike labor costs, the costs of equipment and automation tend to decrease over time (e.g., due to Moore's Law). However, knowledge management of and for workers (i.e., knowledge capture, storage, and transfer) has received insufficient attention in both industries.

The nuclear power industry is particularly challenged with an aging workforce, with massive retirements expected to occur before new workers can attain the full domain knowledge needed for optimal effectiveness and safety. In the medical domain, there remains a steady flow of new clinicians, but the domain knowledge and clinical performance requirements are increasing steadily.

Much knowledge and skill transfer in healthcare still occurs through apprenticeship processes (e.g., student clerkship, internship, residency, and fellowship for physicians; student clinical rotations and new-grad orientations for nurses), in which junior professionals practice under the supervision of more experienced professionals. These processes are unsystematic, and can leave significant gaps in the preparation of these individuals as they take on full responsibility in their areas of practice.

Additional learning and skill acquisition then occurs haphazardly during on-the-job experience on "fee paying customers," i.e., patients. Although the nuclear power industry is required to apply a systems approach to training for individuals in certain job classifications (see 10 CFR 50.120[21]), both domains need to innovate better ways to train and sustain a fully capable workforce to improve human performance while controlling costs.

Professionals in both the nuclear and medical domains operate in large organizations that rely on efficient and effective information exchange among many individuals. Yet, information engineering and data visualization at the system level to support real-time decision making is still repeatedly found to span inadequately disseminated across the entire system (i.e., hospitals, power plants). Critical information for decision making is often distributed across space, time, and people. For instance, the recent death of a 12-year-old boy due to septic shock after hospital discharge was in part due to inadequate information exchange of laboratory results from technicians to physicians.[22] Incidents and accidents associated with "communication failures" in both domains suggest that information exchange at the system level is at times poorly understood or inadequately supported at the organizational level.

For both industries, operators must "visualize" processes at the local and system levels that often cannot be directly sensed. Advances in information engineering and data visualization hold the promise of user interface designs that more effectively transform raw data into usable information so that the processes (e.g., nuclear core, steam, and power generation; human physiology) can be adequately controlled.

However, realizing the benefits of adopting the latest display technology will require more research on and implementation of interface technologies that take advantage of contextual information and sensor fusion (i.e., computerized correlation of different data streams). Similarly, there are opportunities to advance alarm strategies by incorporating contexts into alarm management systems, employing hierarchies of alarm display and annunciation, and providing decision support for alarm conditions.

Yet, despite considerable work and continual attention from both domains, there is no panacea for alarm management. Effective design and implementation of multivariate information displays remain a challenge for both industries despite decades of work by cognitive psychologists within the industries and in analog fields (such as aviation). Perhaps, then, it is not surprising that although there has been considerable academic work on advanced computerized display types and formats in the healthcare and nuclear power domain, there has been little incorporation of these in the marketplace.

Both domains should develop an analysis framework to model actual work practices and information exchanges among personnel in large organizations and to drive the specifications for computerized information systems. For instance, our understanding of teamwork is limited, even in the specific contexts of nuclear power plant main control rooms and operating theaters. Hence, as noted earlier, uncertainties are still associated with what type of CRM or team training is optimal, how often it needs to be conducted, how critical simulation is to the different elements of the training, and the correct mix of training for specific disciplines (or control positions) versus combined team training for all personnel. Further investigation of these and other strategies to improve decision making by individuals and teams would be beneficial to both domains. Analyses of communication need to accommodate frequent updates because work processes are constantly evolving. Design frameworks should help determine which information is most important to present in different contexts.

The nuclear and medical domains both suffer from an "unrocked boat" phenomenon.[23] Operations in both domains can be expected to drift over time away from standard processes that were established to ensure safety. It is also possible that the standard processes once ensuring safety become ineffective as a system evolves. Thus, both domains must not only examine safety risks typified by analysis of the occasional incidents and accidents (i.e., failures) but also monitor the operational capabilities defined by normal or positive outcomes (i.e., successes). In other words, there is a common need to focus on resilience engineering[24,25] to provide flexible and robust design and use of technology and processes rather than an excessively rigid implementation.

Researchers and practitioners may begin improving resilience in two ways. First, both domains need to periodically monitor and revise risk models for developing processes (e.g., in the nuclear power industry these would be created through PRA and HRA), so that resources and procedures can be assigned priorities systematically and dynamically toward areas of highest risk before negative outcomes occur. Second, researchers and practitioners should increase their attention on designing technology that not only attempts to forestall errors but also to make recovery from errors easier, leading to what have been termed "resilient" tools.

FUTURE OPPORTUNITIES AND CHALLENGES

With different lessons to share and common challenges to overcome, near-term opportunities exist to share information between the domains as well as longer-term opportunities to engage in collaborative efforts that would be beneficial to both industries. Such longer-term collaborative efforts could include human factors/human reliability research and standards development.

The two domains should continue to seek opportunities (e.g., the AAMI Clinical Alarm Summit[26]) to share information through a wider range of technical conferences on topics of common interest. Such exchanges could be organized and facilitated by leveraging the resources of professional organizations that have historically supported broad participation (e.g., the Human Factors and Ergonomics Society, Institute of Electrical and Electronics Engineers, National Sleep Foundation) as well as those that have been focused within the respective industries (e.g., the American Nuclear Society, INPO, AAMI, National Patient Safety Foundation, Society for Simulation in Healthcare).

These joint technical meetings could serve as the springboard for collaborative efforts to develop standards or to conduct research in areas with a perceived common need and insufficient technical basis to establish guidelines. The following are promising as topical areas for such initiatives.

- **Interface design.** The healthcare and nuclear power industries could jointly develop user-interface design standards (e.g., IEEE 1289) to design interfaces and technology for a growing range of user populations. For example, new devices are typically built for the global market that encompasses wide variations in culture, age, and familiarity with technology. User interfaces also need to better accommodate personnel who are wearing personal protection equipment (e.g., gloves, surgical face shields, hazmat suits). Display technology and input technologies (gesturing and voice) are ripe areas for future research.
- **Alarm management.** Alarm fatigue is reportedly a growing concern in the healthcare industry. At the same time, the nuclear power domain is undergoing a transition to a broader use of digital technology, creating new possibilities and demands for alarm management. New plants currently under construction and designs currently under NRC review feature highly integrated digital control rooms that will provide operators access to a broader range of sensor inputs than currently available at commercial U.S. nuclear power plants.
- **Simulation.** Both domains employ simulation, although in different ways, with somewhat different goals, and to a widely different extent, for improving system performance and technology development. The two industries can join efforts to develop standards, guidelines, and accreditation

Table 7. Summary of Key Needs

Domain	Research and Implementation Needs
Nuclear Power	1. Methodologies for adopting latest research and technology more quickly without degrading system safety
Medical	1. Methodologies for integrating new technology in a diverse and decentralized decision-making environment 2. Function allocation for systematically distributing work among personnel and technology 3. Methodologies for collecting accident and incident event information that encourages open and honest dissemination without fear of adverse consequences from reporting
Both	1. Knowledge management that can effectively retain and transfer knowledge to maximize performance, improve safety, and decrease costs of operations 2. Systems approach to information engineering and data visualization to facilitate efficient and effective information exchange across many personnel to support better decision making 3. Resilience engineering that can lead to continuous monitoring of risks, periodic updating of risk models, and dynamic allocation of resources for high-risk areas

for simulation facilities and applications. Further, emerging technologies such as augmented/virtual reality could be explored jointly to reduce development costs.

- **Introduction and integration of new technology.** The two domains possess different strengths at introducing new technology in the workplace. The medical domain tends to adopt technology at a relatively high speed while the nuclear power domain tends to be much slower and more systematic. The two domains can work together to develop processes for introducing and integrating new technology that utilize the best aspects of each approach. This is particularly important as both domains are undergoing a phase of rapidly introducing automation into many work processes.

- **Automation.** The many issues of human-automation interaction that have already been identified in academic studies, such as willingness to use, fear of using, and establishment of trust in automated systems, could be further explored in specific contexts and coordination of the two industries. Coordinated research will help identify critical human-automation issues and support the work on methodologies for transferring research findings across domains.

- **Knowledge management.** The two industries urgently need to develop technology for effective knowledge management that enables the transfer of expert knowledge and skills to new personnel to complement their "apprenticeship-style" training with experienced professionals. Both industries rely heavily on domain experts to sustain high levels of performance and safety, but demonstrate limited effort and innovation in accelerating the process of turning novices into experts.

Although the preceding topical areas are of common interest to the healthcare and nuclear power industries, it is important to consider and evaluate the extent to which findings and methods can be effectively applied across the domains. Specific research findings or new technologies may not necessarily be transferable across domains due to differences in specific contextual details. This overarching concern is, itself, a potential area of research. Lessons learned from information exchanges, collaborative efforts, and technology transfers should be compiled and guidelines developed to ensure that information, standards, and technologies are shared across omains in a thoughtful manner that recognizes and respects their important differences.

CONCLUSIONS

Healthcare and nuclear power share the common distinction of being industries where members of the public often take the role of human performance for granted, despite the fact that correct and reliable performance by the professionals and technicians in these industries can so profoundly affect health and safety.

Through extensive training, licensing/certification, and use of standardized work control methods, both industries have historically achieved high levels of reliability. Nevertheless, in both nuclear power and healthcare, most events resulting in adverse outcomes involve some element of degraded human performance. Further analyses of such events reveal that these "failures" in human performance are often the product of identifiable contributing factors that, while often challenging to address, are not intractable.

Taking action to better understand these contributing factors, or "thorniest issues," reduce their incidence in the workplace, and mitigate their adverse effects can yield marked advances in achieving and maintaining the high levels of safety and reliability to which these industries are committed.

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